Exclusive vector meson electroproduction and GPDs

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Outline:

- **Exclusive processes, GPDs, power corrections, parametrization**
- **Analysis of vector meson electroproduction**
- **DVCS**
- **The GPD E**
- **What did we learn about GPDs?**

  (Transverse localization of partons, Ji's sum rule)
- **Summary**

based on work done in collaboration with S. Goloskokov

hep-ph/0501242, 0611290, arXiv:0708.3569, 0809.4126, 0906.0460

Hard exclusive scattering - GPDs

DVCS and meson electroproduction

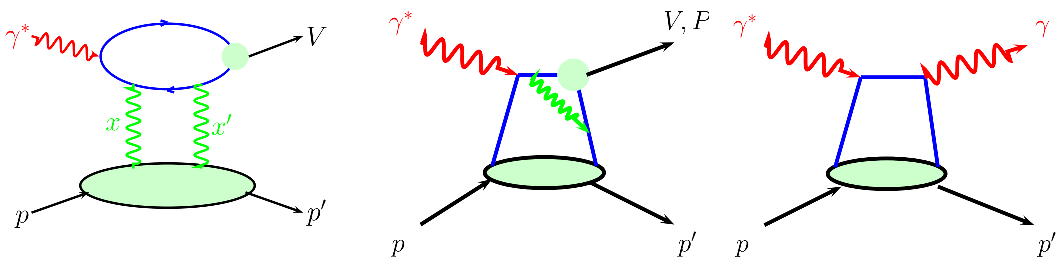
rigorous proofs of collinear factorization in generalized Bjorken regime:

Radyushkin, Collins et al, Ji-Osborne $(Q^2, W \to \infty,\ x_{Bj}$ fixed)

hard subprocesses

$\gamma^* g \to V g\,,$

$\gamma^* q \to V(P,\gamma) q$



and GPDs and meson w.f.

(encode the soft physics)

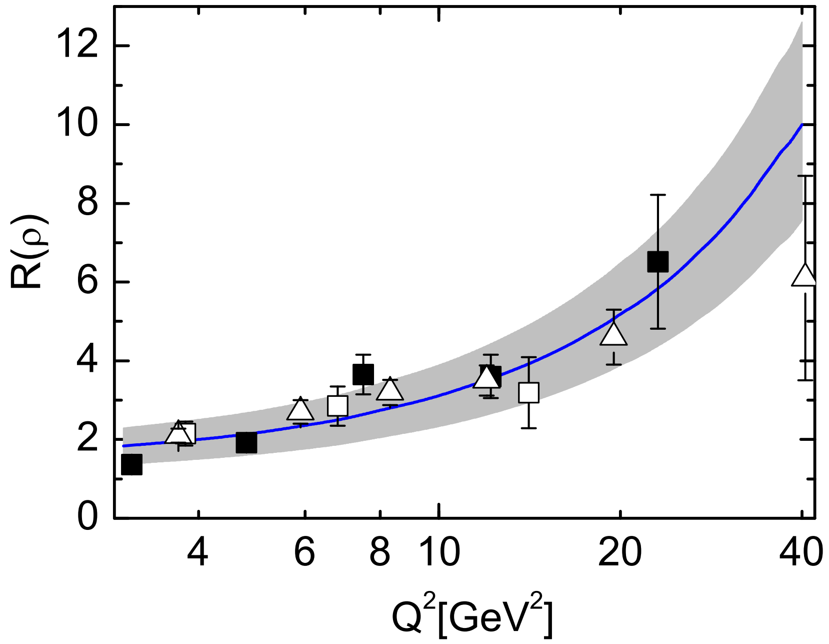
$$\mathcal{M} \sim \int_{-1}^{1} d\bar{x}\, \mathcal{H}(\bar{x},\xi,t) F(\bar{x},\xi,t)$$

dominant transitions $\gamma_L^* \to V_L(P)$, $\gamma_T^* \to \gamma_T$

others power suppressed but often non-negligible (e.g. $\gamma_T^* \to V_T$ large)

Power corrections?

coll. factorization proven for $Q^2 \to \infty$, at finite value there may be power corr.

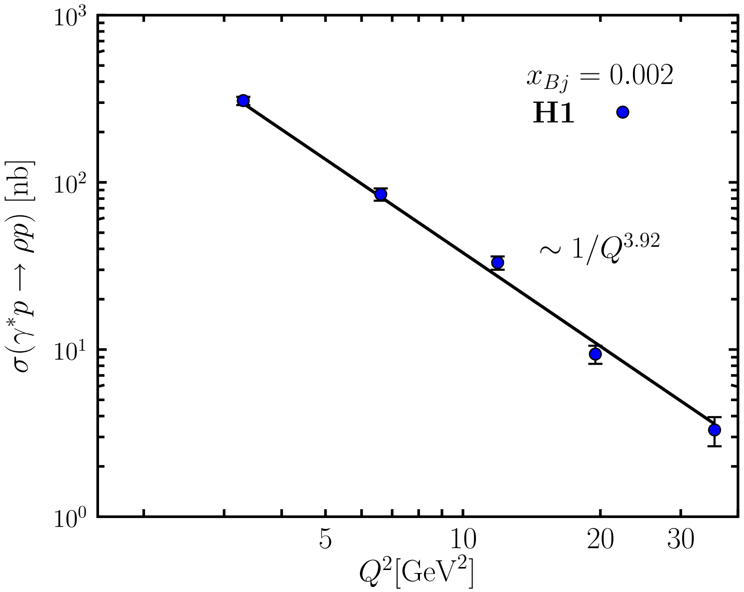


$$R = \sigma_L / \sigma_T$$

data: H1, ZEUS $W \simeq 80\,\mathrm{GeV}$

$\gamma_T^* \to V_T$ transitions substantial

look only to longitudinal cross section?



data H1(09)

collinear factorization:

$\sigma_L \sim 1/Q^6$ at fixed x_{Bj}

Parameterizing the GPDs

double distribution ansatz (Mueller *et al* (94), Radyushkin (99))

$$F_i(\bar{x},\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(\beta+\xi\alpha-\bar{x})\, f_i(\beta,\alpha,t) + D_i\,\Theta(\xi^2-\bar{x}^2)$$

DD: f_i = zero-skewness GPD $\times$ weight fct (generates ξ dep.)

$F(\bar{x},\xi=0,t) = f(\bar{x})\exp\left[(b_f+\alpha_f'\ln(1/\bar{x}))t\right]$

$f = q, \Delta q, \delta^q$ for $H, \widetilde{H}, H_T$ or $c\bar{x}^{-\alpha_f(0)}(1-\bar{x})^{\beta_f}$

Regge-like t dep. (for small ξ and small $-t$ reasonable appr.)

advantage: polynomiality and reduction formulas automatically satisfied

D-term neglected

used in our analysis

Transverse localization of partons

Burkhardt (00): $\xi = 0$ case $\qquad (x = x' = \bar{x})$

Fourier transform:

$$q(x, \xi = 0, \mathbf{b}) \,=\, \int \frac{d^2\mathbf{\Delta}}{(2\pi)^2}\, e^{-i\mathbf{b}\cdot\mathbf{\Delta}}\, H^q(x, \xi = 0, t = -\Delta^2)$$

and analogously for the other GPDs

$q(x, \xi = 0, \mathbf{b})$ gives probability to find a quark q with long. momentum fraction x at transverse position $\mathbf{b}$ (seen in an IMF)

$$\sim \exp\left[t g_h(x)\right] : \qquad q(x, \xi = 0, \mathbf{b}) \,=\, \frac{1}{4\pi}\frac{q(x)}{g_h(x)}\, \exp\Big[-\frac{b^2}{4 g_h(x)}\Big]$$

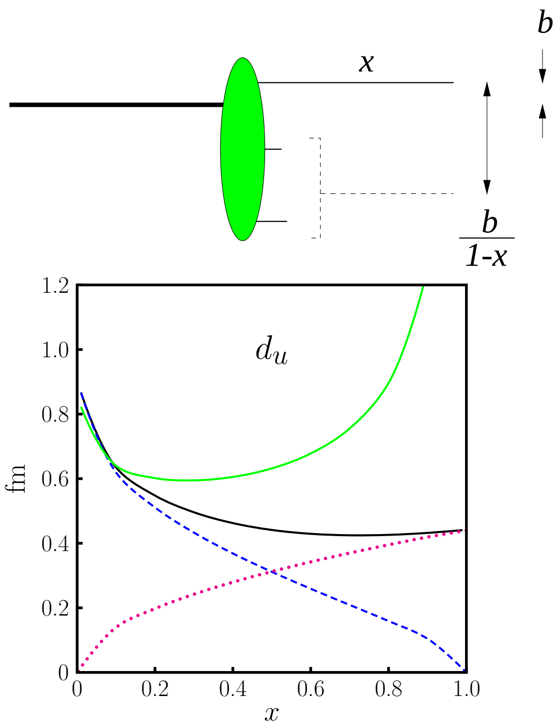
Transverse size of the proton

Diehl $et\ al$ (04): analysis of nucleon form factors

more complicated profile function required for large x, large $-t$

$$\exp\left[g_h(x)t\right]: \qquad g_h = (b_h + \alpha' \ln 1/x)(1-x)^3 + Ax(1-x)^2$$

strong $x \leftrightarrow t$ correlation, small x (small $-t$): $\quad g_h \longrightarrow$ Regge profile fct



FT:

center of momentum $\sum x_i \mathbf{b}_i = 0$

$\mathbf{b}$ transv. distance of struck parton

$\mathbf{b}/(1-x)$ distance between struck parton

and spectator system

provides estimate of size of hadron

$d^2(x) = \langle b^2 \rangle_x / (1-x)^2 = 4g_h(x)/(1-x)^2$ for u

quarks: Regge-like $\quad (1-x)^3 \quad (1-x)^2$ term

The $\gamma^* p \to VB$ amplitudes

consider large Q^2, W and small t;
kinematics fixes skewness: $\xi \simeq \frac{x_{\rm Bj}}{2-x_{\rm Bj}}[1+m_V^2/Q^2] \simeq x_{\rm Bj}/2 +$ m.m.c.

$$\mathcal{M}_{\mu+,\mu+}(V) = \frac{e_0}{2}\left\{\sum_a e_a \mathcal{C}_V^{aa}\langle H_{\rm eff}^g\rangle_{V\mu} + \sum_{ab}\mathcal{C}_V^{ab}\langle H_{\rm eff}^{ab}\rangle_{V\mu}\right\},$$

$$\mathcal{M}_{\mu-,\mu+}(V) = -\frac{e_0}{2}\frac{\sqrt{-t'}}{M+m}\left\{\sum_a e_a \mathcal{C}_V^{aa}\langle E^g\rangle_{V\mu} + \sum_{ab}\mathcal{C}_V^{ab}\langle E^{ab}\rangle_{V\mu}\right\},$$

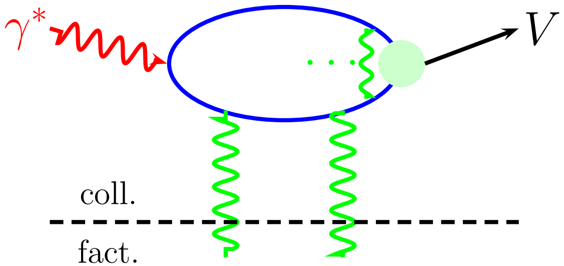
$\mathcal{C}_V^{ab}$ flavor factors, $M(m)$ mass of $B(p)$, $H_{\rm eff} = H - \xi^2/(1-\xi^2)E$
contributions from $\widetilde{H}$ to T-T amplitude not shown
electroproduction with unpolarized protons at small ξ:
E not much larger than H (see below) $\Longrightarrow H_{\rm eff} \to H$ for small ξ
$|M_{\mu-,\mu+}|^2 \propto t'/m^2$ neglected $\Longrightarrow$ probes H (exception ρ^+)
trans. polarized target: probes $Im[\langle E\rangle^*\langle H\rangle]$ interference
polarized beam and target: probes $Re[\langle H\rangle^*\langle \widetilde{H}\rangle]$ interference

Subprocess amplitudes

$F = H, E$ λ parton helicities

$$\langle F\rangle^{ab(g)}_{V\mu} = \sum_\lambda \int d\bar{x}\mathcal{H}^{Vab(g)}_{\mu\lambda,\mu\lambda}(\bar{x},\xi,Q^2,t=0)\,F^{ab(g)}(\bar{x},\xi,t)$$

$F^{aa} = F^a\,,\qquad F^{ab} = F^a - F^b \quad (a \neq b)$ (with flavor symmetry)



$$\mathcal{H}^{Vab}_{\mu\lambda,\mu\lambda} = \int d\tau d^2b\,\hat{\Psi}_{V\mu}(\tau,-\vec{b})\exp[-S(\tau,\vec{b},Q^2)]$$
$$\times\quad \hat{\mathcal{F}}^{ab}_{\mu\lambda,\mu\lambda}(\bar{x},\xi,\tau,Q^2,\vec{b})$$

LO pQCD

+ quark trans. mom.

+ Sudakov supp.

$\Rightarrow$ lead. twist for $Q^2 \to \infty$

Sudakov factor (Sterman et al)

$S \propto \ln \frac{\ln(\tau Q/\sqrt{2}\Lambda_{QCD})}{-\ln(b\Lambda_{QCD})}$ + NLL

$\hat{\mathcal{F}}$ FT of hard scattering kernel

e.g. FT of $\propto e_a/[k_\perp^2 + \tau(\bar{x}+\xi)Q^2/(2\xi)]$

regularizes also TT amplitude

$$\mathrm{TT}: \int_0^1 d\tau \frac{\Phi_V(\tau)}{\tau}\frac{1}{\mathbf{k}_\perp^2 + c\tau Q^2}$$

in collinear appr – IR singular

Goloskokov-K. 06, 07, 08, 09:

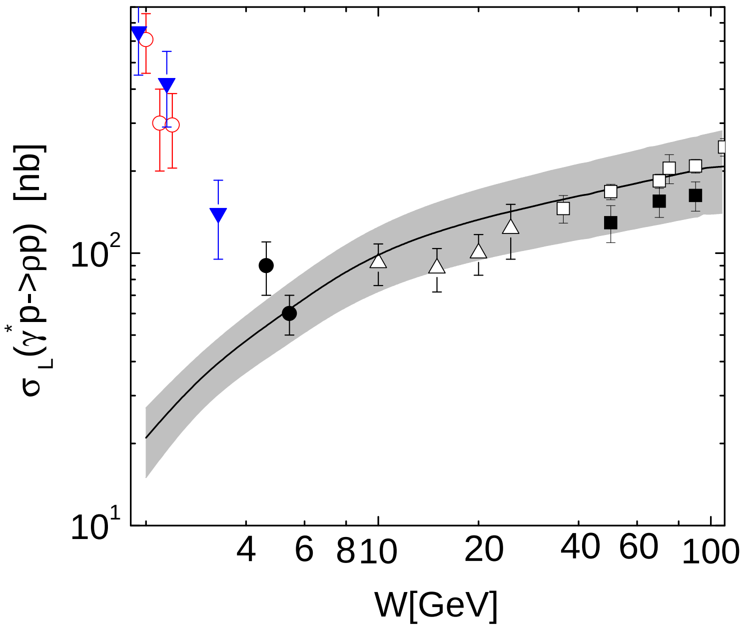
analysis of cross sections and spin density matrix elements
for ρ^0 and ϕ electroproduction
data taken from HERMES, COMPASS, E665, H1, ZEUS
cover large range of kinematics $Q^2 \simeq 3 - 100\,\mathrm{GeV}^2 \quad W \simeq 5 - 180\,\mathrm{GeV}$

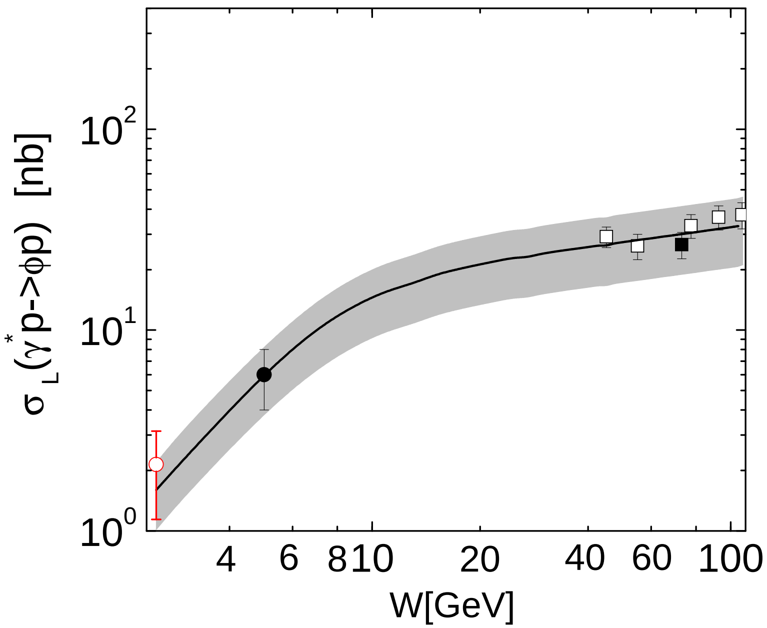
H constructed from CTEQ6 PDFs through the double distr. ansatz
($D = 0$, sum rules and positivity bounds checked numerically)

Gaussian wave fcts for the mesons $\quad \Psi_{Vj} \propto \exp\big[-a_{Vj}^2 k_\perp^2/(\tau\bar{\tau})\big]$
main features of H seems fairly well determined at small ξ and $x \lesssim 0.6$

(bears resemblance to color dipole model:
Frankfurt et al (95), Nikolaev et al(11), Anikin(11))

ρ^0 and ϕ cross sections





at $Q^2 = 4(3.8)\,\mathrm{GeV}^2$ E665 (△), HERMES (●), CORNELL (▲)

ZEUS (□), H1 (■), CLAS (○)

Goloskokov-K (09)

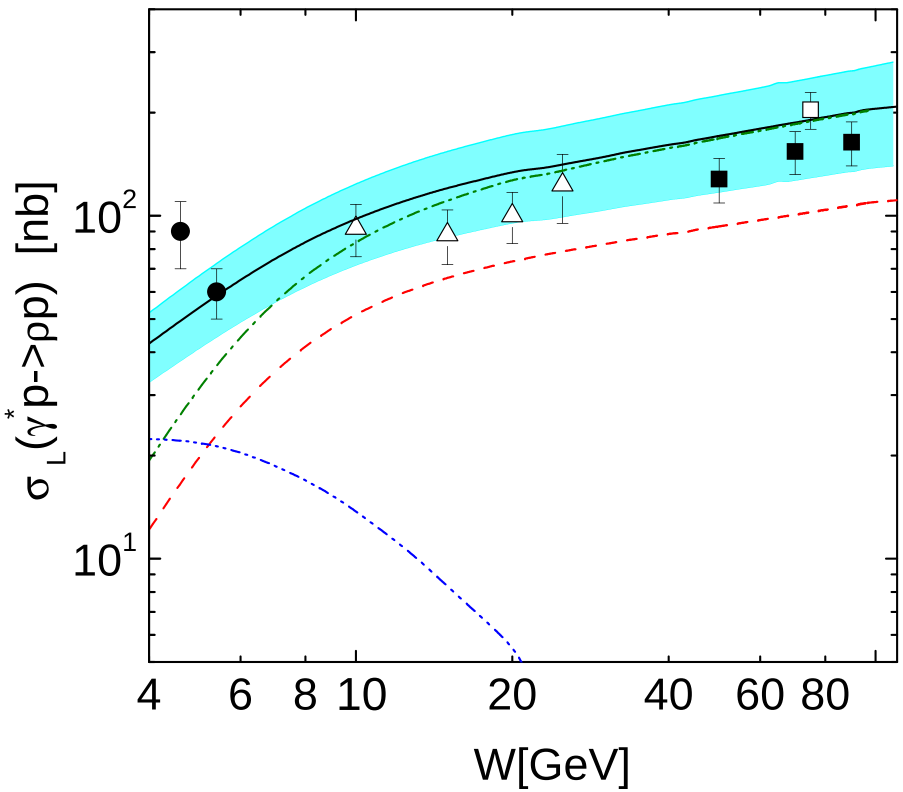
ω, ρ^+ very large at small W too CLAS (most likely val. quarks responsible)

double distrib. ansatz too simple for valence quarks at large ξ? (resonances?)

breakdown of handbag physics?

JLAB12 may explore region close to minimum

GPD composition



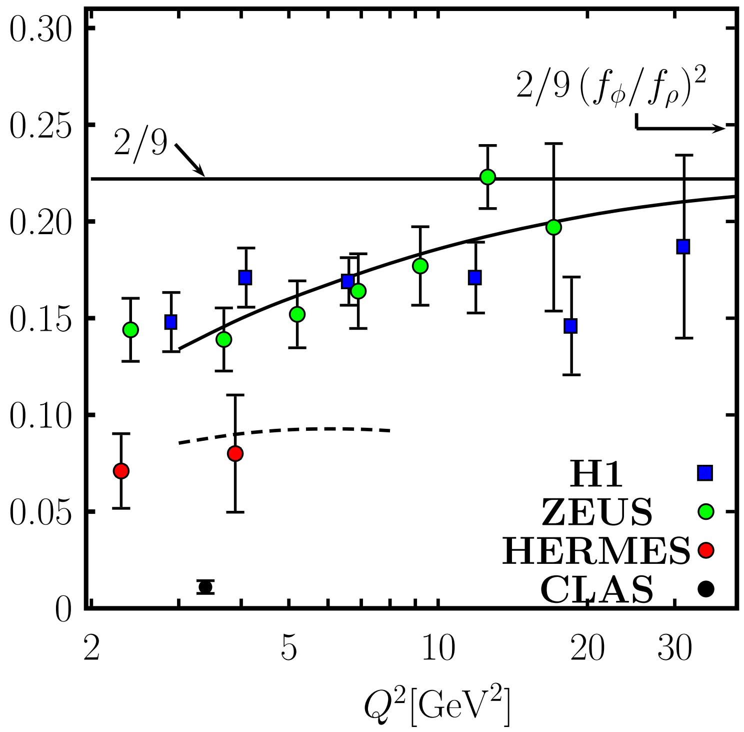
$Q^2 = 4\,\mathrm{GeV}^2$,

glue+sea, glue, valence +interf.

gluons (+ sea) dominant
for COMPASS kinematics

data: H1 (open), ZEUS (filled squares), E665 (triangles), HERMES (circles)

$\sigma_L(\phi)/\sigma_L(\rho^0)$



HERA: $W \simeq 80\,\text{GeV}$
HERMES: $W = 5\,\text{GeV}$

CLAS: $W \simeq 2.2\,\text{GeV}$

suppression due to different a_V

SU(3) breaking in sea $\kappa_s = \frac{(u(x)+d(x))/2}{s(x)}$ CTEQ6

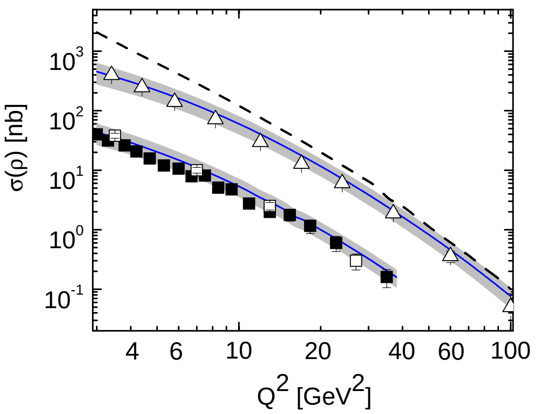
$\kappa_s \simeq 2$ at low Q^2 and $\to 1$ for $Q^2 \to \infty$

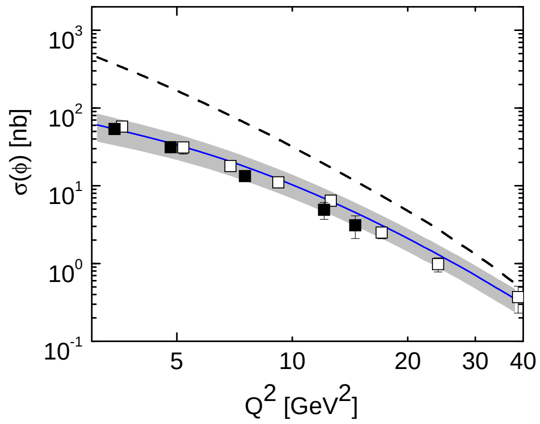
and valence quarks for HERMES, CLAS

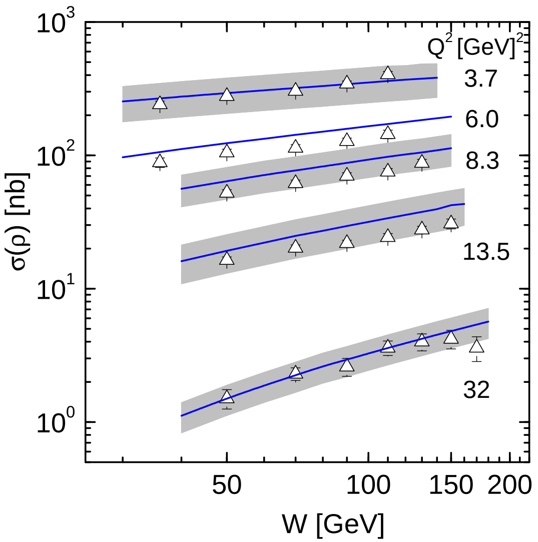
COMPASS data on ρ^0 and ϕ may verify dominance of gluons ($+$ sea)

JLAB12: checks sea

Results on cross sections







ρ^0: $W = 90, 75\,\text{GeV}$
(latter divided by 10)
ϕ: $W = 75\,\text{GeV}$

open (filled) symbols:
ZEUS (H1)

σ_L/σ_T shown before
SDME

DVCS

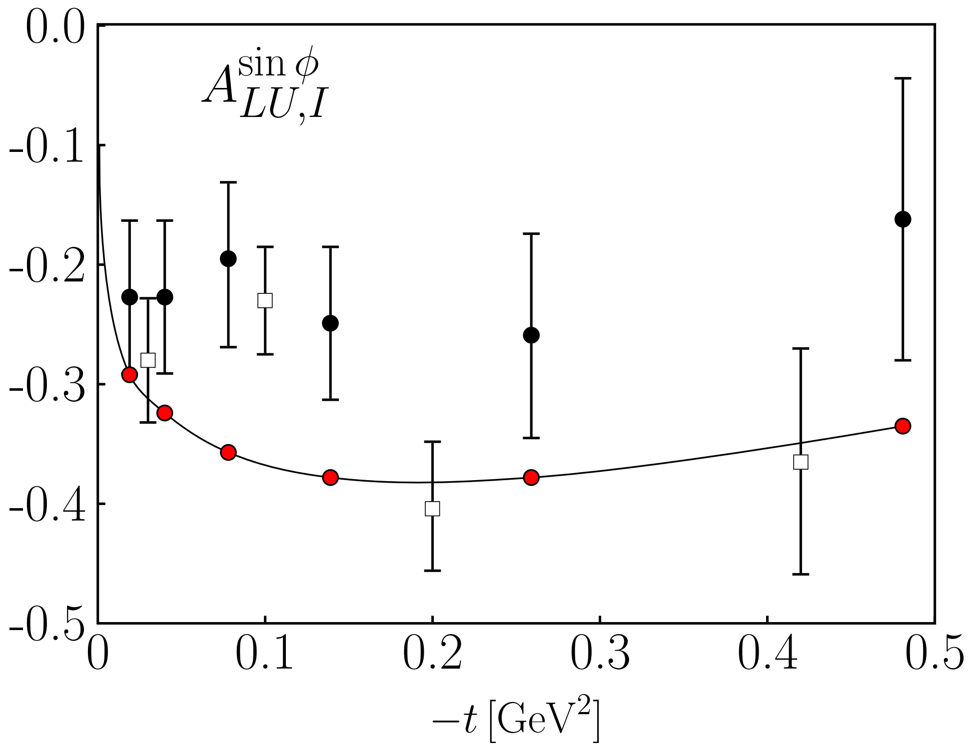
Exploiting universality:
applying a given set of GPDs determined in either DVCS or meson electroproduction, to the other process predictions

Kumericky *et al* (11), Meškauskas-Müller (11)

set of GK GPDs applied to DVCS at HERA kinematics in a LO collinear calculation

(compatible with GK approach to meson prod.)

Moutarde-Sabatie (K) in progress
using GK GPDS –first results show reasonable agreement
some difficulties for Jlab kinematics (large skewness, small W, small Q^2)



beam spin asymmetries

Data: ● HERMES (09) (contaminated by resonance contributions)

□ HERMES (11) (prel. recoil data)

$\langle Q^2 \rangle = 2.37\,\mathrm{GeV}^2$

$\langle x_{\mathrm{Bj}} \rangle = 0.09$

Moutarde-Sabatie (prel.) ● using GK GPDs

HERMES beam spin, beam charge and target spin asymmetries in general well described with a few exceptions (like the above example, wait for recoil data)

asymmetries dominated by H, other GPDS ($\widetilde{H}, E$) can be neglected

exception $A_{UT,DVCS}^{\sin(\phi-\phi_s)}$ (see below)

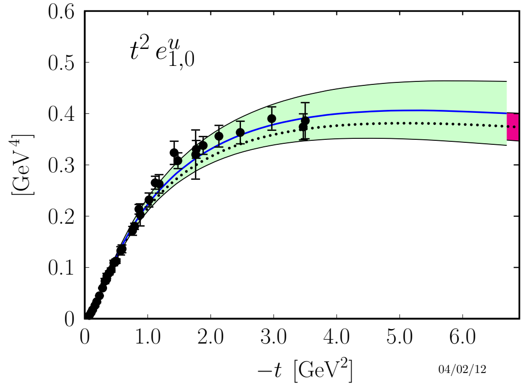
What do we know about E_v?

analysis of Pauli FF for proton and neutron at $\xi = 0$ Diehl et al (04):

$$F_2^{p(n)} = e_{u(d)} \int_0^1 dx E_v^u(x, \xi = 0, t) + e_{d(u)} \int_0^1 dx E_v^d(x, \xi = 0, t)$$

ansatz: $E_v^a = e_v^a(x) \exp\left[t g_v^a(x)\right]$ $e_v^a = N_a x^{-\alpha_v(0)}(1-x)^{\beta_v^a}$ (like PDFs)

N_a fixed from $\kappa_a = \int_0^1 dx E_v^a(x, \xi = 0, t = 0)$



fits to FF data: $\beta_v^u \simeq 4$, $\beta_v^d = \beta_v^u + 1.6$

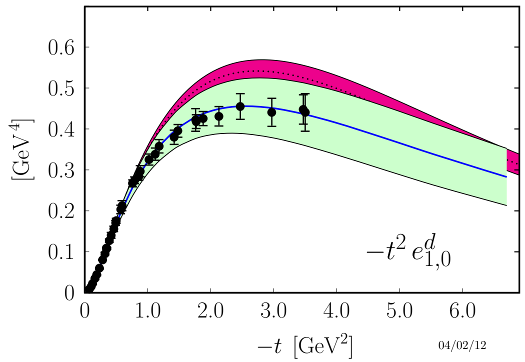
(other powers not excluded in 04 analysis)

new JLab data on $G_{E,M}^n$

up to $3.5(5.0)\,\mathrm{GeV}^2$, favor $\beta_v^u < \beta_v^d$

$\beta_v^u \simeq 4.5$, $\beta_v^d \simeq 6$ (preliminary)

Input to double distribution ansatz



E for gluons and sea quarks

Diehl-Kugler(07), GK(09)

sum rule (Ji's s.r. and momentum s.r. of DIS) at $t = \xi = 0$

$$\int_0^1 dx x e_g(x) = e_{20}^g = -\sum e_{20}^{a_v} - 2\sum e_{20}^{\bar{a}}$$

valence term very small, in particular if $\beta_v^u \leq \beta_v^d$

$\Rightarrow$ gluon and sea quark moments cancel each other almost completely

positivity bound for FT forbids large sea $\Longrightarrow$ gluon small too

$\frac{b^2}{m^2}\left(\frac{\partial e_s(x,b)}{\partial b^2}\right)^2 \leq s^2(x,b) - \Delta s^2(x,b)$

forw. limits (flavor symm. sea for E assumed): $\quad e_i = N_i x^{-\alpha_g(0)}(1-x)^{\beta_i}$

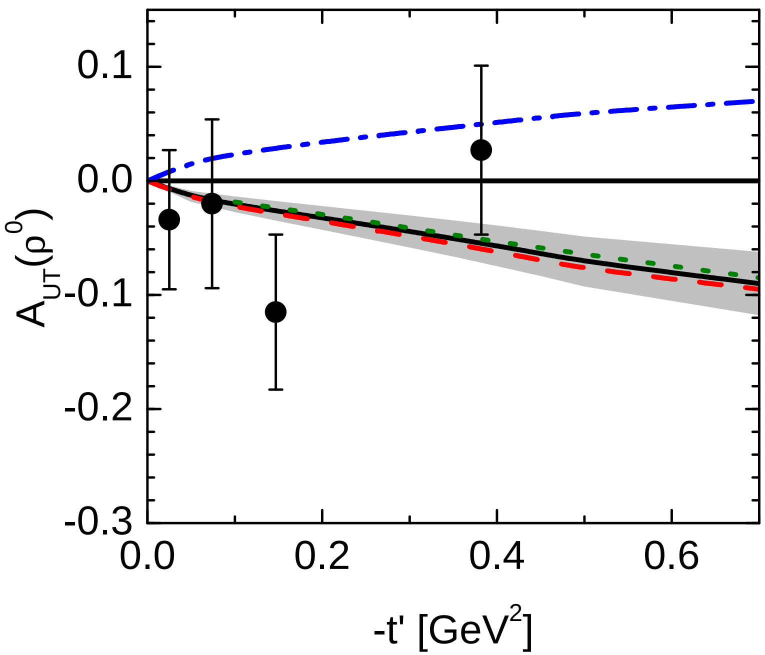
and Regge-like t dependence: $\quad \propto \exp\left[t\left(\alpha_i' \ln(1/x) + b_i^e\right)\right]$

N_s fixed by saturating bound, N_g from sum rules, $\alpha_g = 0.1 + 0.15t$

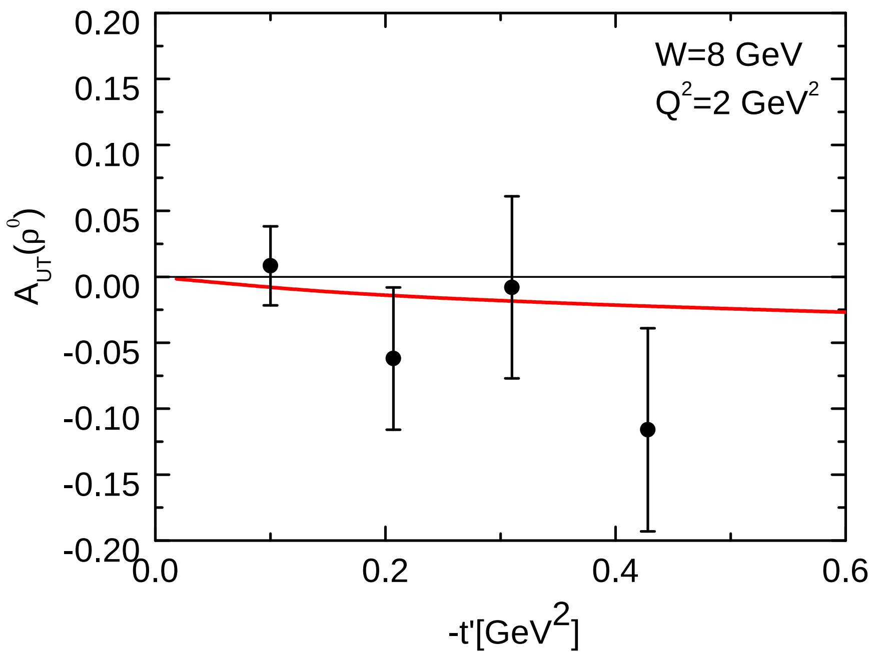
input to double distribution ansatz

Results for $A_{UT}(V)$

data: HERMES (08)



COMPASS prel.



$W = 5\,\mathrm{GeV} \quad Q^2 = 3\,\mathrm{GeV}^2$ $\qquad$ $W = 8\,\mathrm{GeV} \quad Q^2 = 2\,\mathrm{GeV}^2$

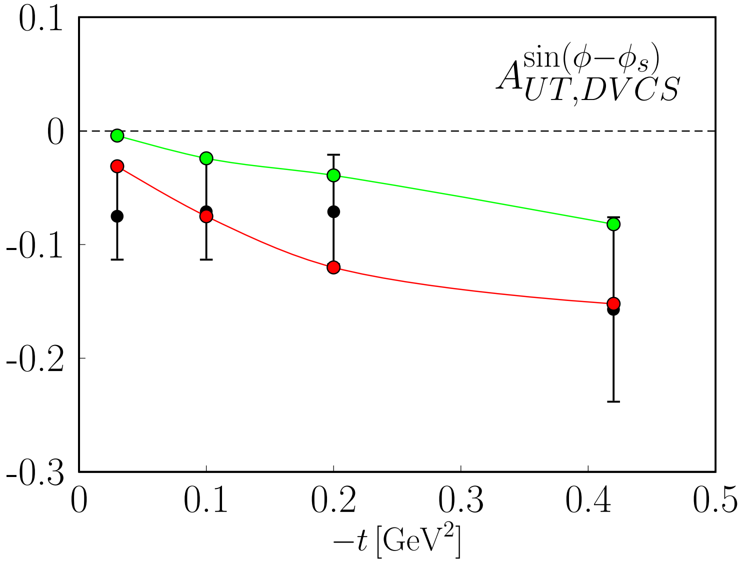
$N_s = N_g = 0$, $\beta^g = 6, \beta_s = 7$ $N_s > 0$, $\qquad$ $N_s = N_g = 0$

$N_s < 0$, $\beta_v^u = 10 > \beta_v^d$ (ruled out by new FF analysis)

$A_{UT}(\phi) \simeq 0$ prel. HERMES data: $A_{UT} = -0.05 \pm 0.12$ (integrated)

(E for gluons and sea small and partial cancellation)

Target asymmetry in DVCS



data: HERMES 06 $\langle Q^2 \rangle \simeq 2.7\,\mathrm{GeV}^2$, $\langle x_{\mathrm{Bj}} \rangle \simeq 0.1$

$$A_{UT,DVCS}^{\sin(\phi-\phi_s)} \sim \mathrm{Im}\Big[\langle E \rangle^* \langle H \rangle\Big] \qquad \propto \sqrt{-t'}$$

E necessary

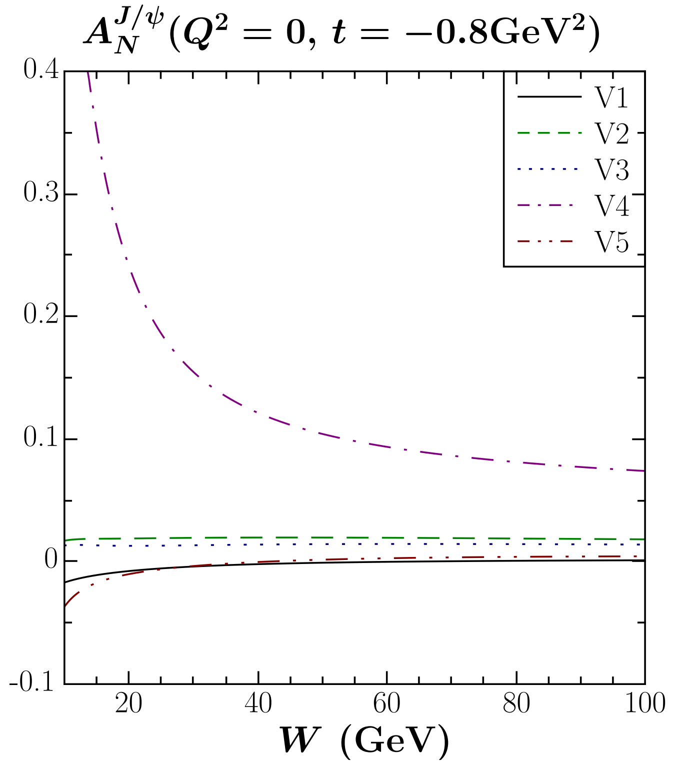
Moutarde-Sabatie (K) (• $N_s < 0$, $\beta_s = 7$, flavor symm. sea)

no recoil data from HERMES (• $N_s > 0$)

E^g?

not much known about E^g and E^s

Possibility: $A_{UT} = A_N$ for photoproduction of J/Ψ Koempel et al (11)



dominated by gluonic GPDs

intrinsic charm small

A_N generally small because

$|\langle E^g \rangle| \ll |\langle H^g \rangle|$ and small phase diff.

Diehl (10): node in E^g may lead to larger A_N, e.g. of order 10% for $x_0 = 0.05$

will affect electroproduction of ϕ as well (gluonic and strange GPDs)

- large A_N in J/Ψ most likely leads also to large asymmetry in ϕ production

e.g. for $x_0 = 0.05$: $A_{UT} = 0.15$ (integrated over t)

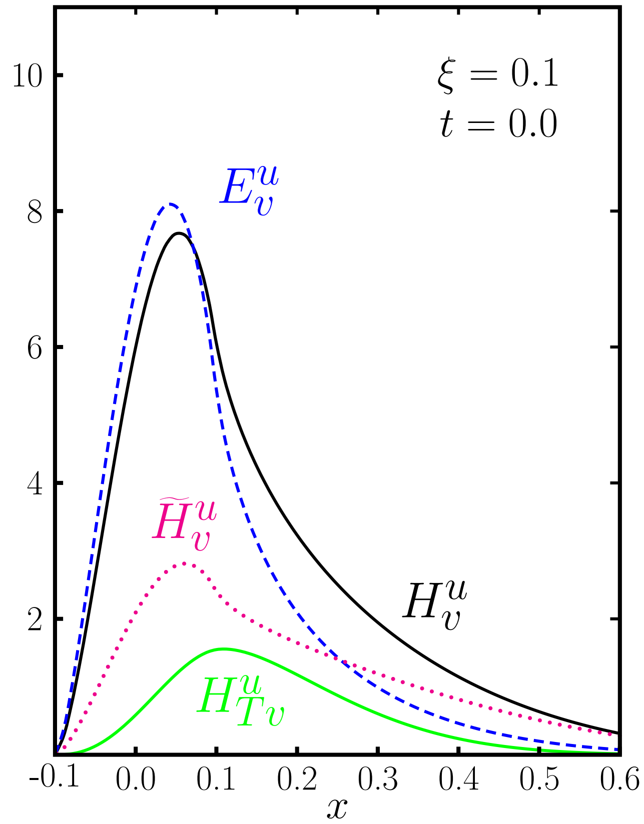
What did we learn about GPDs from meson production?

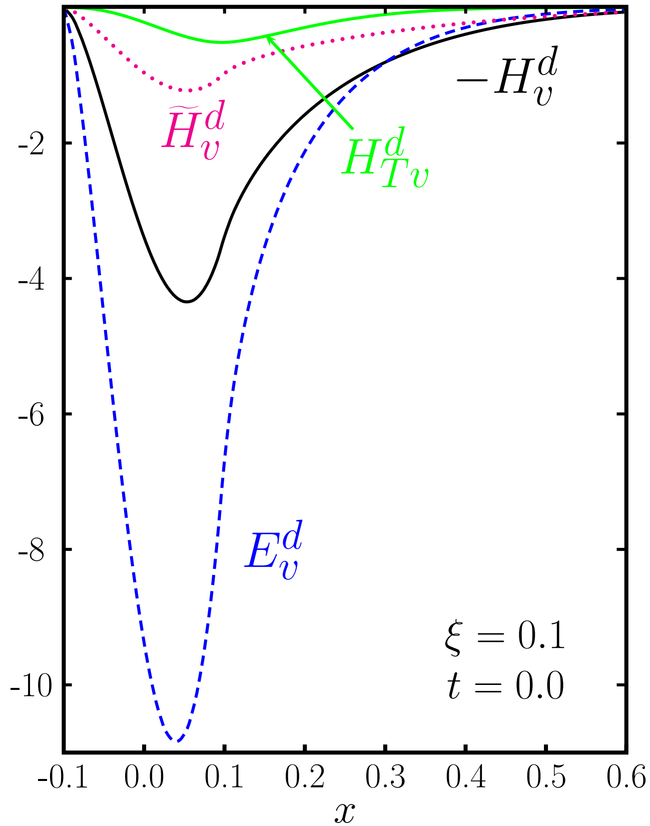
GPD	probed by	constraints	status
H	ρ^0, ϕ cross sections	PDFs	***
$\widetilde{H}$	$A_{LL}(\rho^0)$	polarized PDFs	*
E	$A_{UT}(\rho^0, \phi)$	sum rule for 2^{nd} moments	*
$\widetilde{E}, H_T, \ldots$	-	-	-
H	ρ^0, ϕ cross sections	PDFs, Dirac ff	***
$\widetilde{H}$	π^+ data	pol. PDFs, axial ff	**
E	$A_{UT}(\rho^0, \phi)$	Pauli ff	**
$\widetilde{E}^{n.p.}$	π^+ data	pseudoscalar ff	*
H_T	π^+ data	transversity PDFs	*
$\widetilde{H}_T, E_T, \widetilde{E}_T$	-	-	-

Status of small-skewness GPDs as extracted from meson electroproduction data. The upper (lower) part is for gluons and sea (valence) quarks. Except of H for gluons and sea quarks all GPDs are probed for scales of about $4\,\mathrm{GeV}^2$

PDFs *****

Valence quark GPDs





	H	E	$\widetilde{H}$
u_v	2	$\kappa_u = 1.67$	0.93
d_v	1	$\kappa_d = -2.03$	-0.34

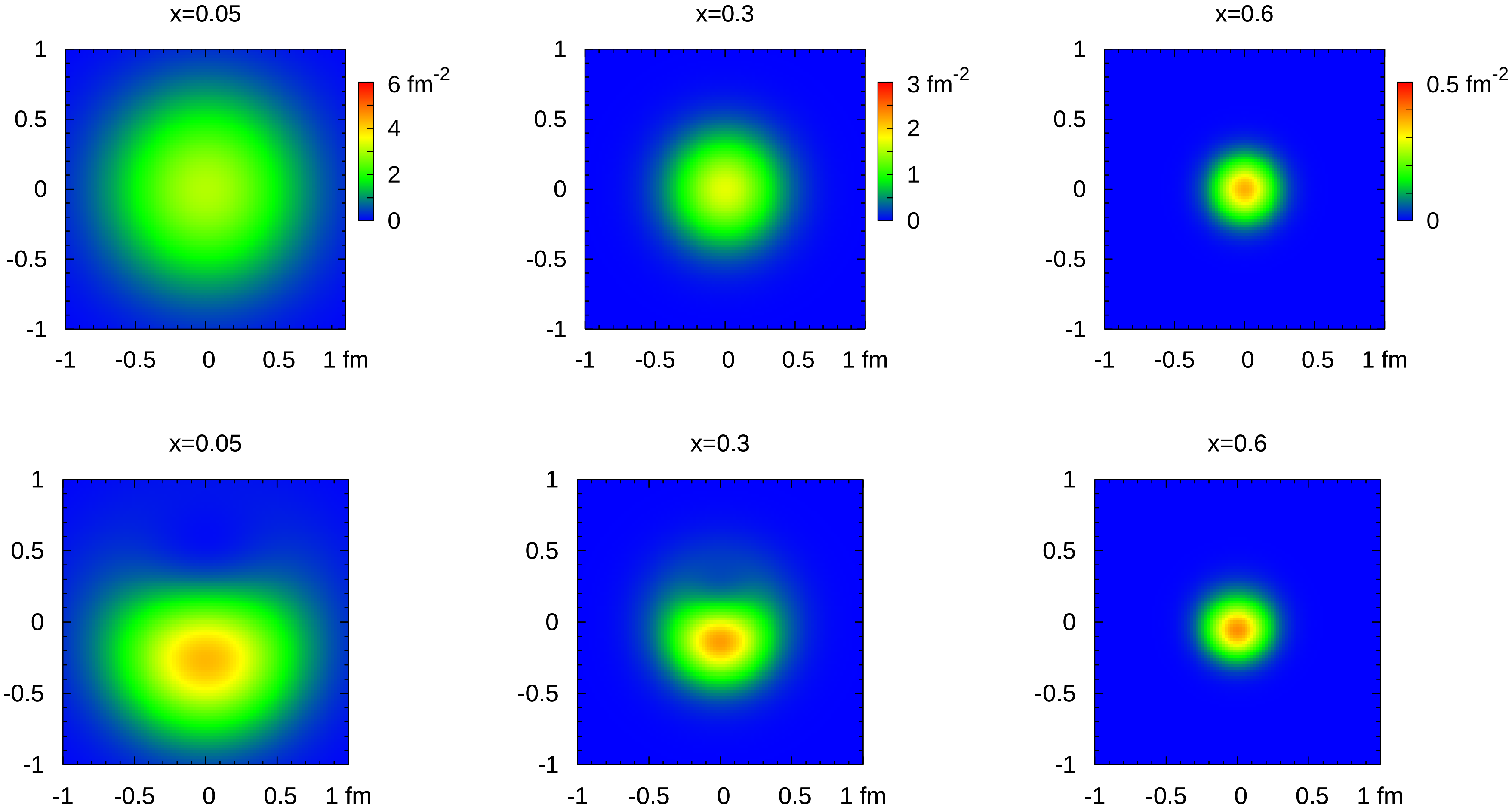
lowest moments at $t = 0$

fix signs and rel. sizes

if GPDs have no nodes and

similar t dependence

Tomography of d_v graphs



$$q_v^X(x,\mathbf{b}) = q_v(x,\mathbf{b}) - \frac{b^y}{m}\frac{\partial}{\partial \mathbf{b}^2} e_v^q(x,\mathbf{b})$$

e_v contains non-zero orbital angular momentum Diehl et al (04)

Ji's sum rule

$$\langle J^a \rangle = \frac{1}{2}\Big[q^a_{20} + e^a_{20}\Big] \qquad \langle J^g \rangle = \frac{1}{2}\Big[g_{20} + e^g_{20}\Big] \qquad (\xi = 0)$$

for the variants discussed in context of A_{UT}: using CTEQ6 PDFs

$$\begin{array}{llll} J^u = 0.250 & J^d = 0.020 & J^s = 0.015 & J^g = 0.214 \\ = 0.276 & = 0.046 & = 0.041 & = 0.132 \\ = 0.225 & = -0.005 & = -0.011 & = 0.286 \end{array}$$

J^i quoted at scale $4\,\mathrm{GeV}^2$, $\sum J^i \simeq 1/2$, the spin of the proton

characteristic, stable pattern: for all variants J^u and J^g are large, others small

$$\langle J^{u_v} \rangle = 0.208(6) \qquad \langle J^{d_v} \rangle = -0.011(11)$$

(prel. from new form factor analysis)

Lattice (Hägler et al (07)): $\langle J^u \rangle = 0.214(27)\,,\ \langle J^d \rangle = -0.001(27)$, ($m_\pi$(phys))

orbital angular momenta: subtract contribution from spin

$$\langle L^i \rangle := \langle J^i \rangle - \Delta q^i/2 \qquad \langle L^{u_v} \rangle \simeq -0.255(6) \quad \langle L^{d_v} \rangle \simeq 0.160(11)$$

Summary

- exclusive electroproduction of vector mesons allows to extract the GPD H rather well at small ξ and $W \gtrsim 4\,\mathrm{GeV}$
- information on E, from A_{UT} less precise, for valence quarks not too bad due to form factor constraint
- double distr. ansatz is flexible enough to account for all small ξ data
- gluon and sea-quark sector almost unknown (exception H), no experimental information as yet
- the GPDs allows to predict DVCS, results in fair agreement with experiment
- the GPDs allow to study transverse localization of partons (at least for valence quarks) and to evaluate Ji's sum rule
- open question with large ξ region: does handbag physics still apply or have the GPD parameterizations to be improved at large ξ?
  (see failure with $\sigma_L(\rho^0)$)